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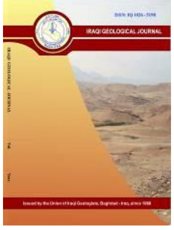

Groundwater Vulnerability Analysis via GALDIT-GIS Method to Seawater Intrusion, South of Iraq

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Abstract

One of the most significant environmental problem that needed to be identified and managed is the intrusion of salty water into the aquifers. Human actions, such as excessive irrigation pumping, as well as the rising sea level, have generated a vulnerable state for seawater intrusion into aquifers. Six effective factors have been focused on evaluating seawater intrusion of groundwater Dibdibba aquifer in Basrah, south of Iraq mainly based on the GALDIT-GIS model involving the groundwater occurrence, aquifer hydraulic conductivity, groundwater levels above sea level, distance to shoreline, impact the existing status of seawater intrusion, and thickness of the aquifer. Water samples were collected for 19 wells over the area concerned. Chemical parameters including SO_4^{2-}, Cl^-, and Total Dissolved Solids were applied for modeling in addition to measuring depth to groundwater level. The results of the GALDIT model showed that the Dibdibba aquifer revealed three levels of vulnerabilities arranged according to risks: a high level which occupied Umm Qasr area and the near distance of Khor Al-Zubair to shoreline with an area of 76.87 Km^2 and 82.56 Km^2, moderate level represented the long distance of Khor Al-Zubair to shoreline and Safwan areas about 205.21Km^2 and 196.61 Km^2, and low level represented Al-Muwailihat area with 139.65Km^2 and 142.61 Km^2 for the wet and dry season, respectively.

Keywords: GALDIT rating; Vulnerability scores; Intrusion impact; Dibdibba; Iraq

1. Introduction

Everywhere in the world, the depletion of the groundwater resources close to coastal places has been markedly raising in recent decades for the purpose of agricultural, industrial, and economic investments, particularly in arid and semi-arid zones that characterized with scarce of rivers, low rainfall and high evaporation rates. The changes such reducing of water table and poor recharge rate, the hydrological system of coastal zones and other geo-environmental factors naturally lead to vulnerability of aquifers (Seenipandi et al., 2019). Water consumption with environmental health problems are significantly developing among communities that lack to environmental awareness (Awadh, 2018). The bad agricultural practices that use overexploitation of groundwater for irrigation lead to lowering water levels and capturing saline water into groundwater. Climate change and its relation with recharge has a strong influence on groundwater level variability (Awadh et al., 2021). Intrusion of seawater (IOSW) into aquifers is one of the most significant problems of water contamination that is associated with

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several factors, including anthropogenic activities such intensive pumping, adverse effects of climate change such sea-level rise and intense drought, which allow the transfer of saltwater to aquifers and cause changes in the quantity and quality of groundwater (Parizi et al., 2019). Not only geomorphological features but also geochemical and climate change are contribute to variable of water quality (Al-Sumaidai and Al-Kubaisi, 2021). The low topography of coastal lands is also an additional factor for seawater intrusion (Satishkumar et al., 2016). Actually, the IOSW indicates the hazards expected to a specific region and the extent to which it is exposed to the threat of intrusion based on certain features associated with the same area (Gangadharan and Rekha, 2015). It effectively depends on groundwater levels, seawater channels, aquifer geologic structure and its hydrogeological characteristics (Zamroni et al., 2021). The determining of vulnerability of groundwater to natural and human activities occurs through identifying areas that have been exposed to transport of saltwater by environmental monitoring, land-use planning and control of groundwater level changes and reduction of water pollution (Bouderbala et al., 2016). As a result, several hydrogeological researches have been care on contaminating of seawater problem depending on the area of the study and type of data used to evaluate the aquifer vulnerability (Table 1).

Table 1. Concise of some studies deal with the vulnerability mapping of coastal aquifers to IOSW

References	**Application**	**Area concerned**	**Validation by**
Mahesha et al. (2012)	GALDIT	Western India	Cl^-/HCO_3^-
Bouderbala et al. (2016)	GALDIT, AVI	Northern Algeria	WQI[1]
Trabelsi et al. (2016)	GALDIT, GQI_{SWI}	Tunisia	JR[2], Cl^-, and TDS[3]
Mahrez et al. (2018)	GALDIT	NE-Algeria	-
Kardan et al. (2017)	GALDIT, DRASTIC	Northern Iran	NO_3^-, Na^+, Cl^-, and TDS
Seenipandi et al. (2019)	GALDIT	Southern India	TDS, Cl^-, $HCO3^-$, and $Cl^-/HCO3^-$
Parizi et al. (2019)	GALDIT, GAiDIT, GALDIT-i	Northern Iran	f_{sea}[4], GQI[5] L_X[6], and TDS
El Fehri et al. (2021)	GALDIT, SINTACS, DRASTIC, RIHM	Tunisia	TDS and EC[7]

[1] Water Quality Index; [2]Jones Ratio (Na/Cl); [3]Total Dissolved Solids (TDS); [4]Fraction of seawater in coastal aquifer; [5]Groundwater Quality Index; [6]Length of seawater intrusion at point x from shoreline; [7]Electrical Conductivity.

Previous geoscience studies have dealt with the IOS within Dibdibba aquifer. Such as Al-Musawi and Khorshid (2013) applied the Vertical Electrical Sounding method (VES) using the Schlumberger array to detect electrical resistivity; it concluded that apparent electrical resistivity values decreased with depth, especially in periods of unregulated intense pumping because of increasing salinity of the groundwater at these periods, Also decreased the true resistivity values in the eastern part in Khor Al-Zubair resultant from the high salinity that probably comes from the sea, and away from Khor Al-Zubair, the groundwater belongs to the marine origin of brackish type. According to Al-Suraifi (2015), the SEAWAT model was used for detecting the IOSW in Umm Qasr wells, the model applied to calibrate and simulate the density of groundwater and the transportation of solutes in the aquifers, the results of modeling showed a minor sensitivity to specific yield and diffusion parameters, and major sensitivity for change in the recharge and pumping rates, the modeling showed that Umm Qasr is the most affected area to seawater and perhaps increasing the intrusion upon the next nineteen years by the prediction of pumping test in the future. Abdulameer et al. (2018) discussed the salination of the Dibdibba aquifer among Al-Zubair, Safwan, and Umm Qasr areas by applying the electrical resistivity 2D imaging, three resistivities of 2D within Dibdibba aquifer have been resulted, the confined aquifer showed low resistivity zone and the TDS values of groundwater had been tested from 15000-30000 mg/l which indicated the saline water, while the high part of unconfined aquifer displayed very low resistivity zone which explained the intrusion of saltwater from Khor Al-Zubair channel to that part of unconfined aquifer, as for the lower part of unconfined aquifer tended to brackish water owing to the TDS values scored from 10000-15000 mg/l that had high to medium resistivity zone. Also, Abdulameer et al. (2021) studied the seawater intrusion by analyst the ratio of Cl^-/Br^- and SO_4^{2-} in the same area. the rsults showed that IOSW effect extends only to about 8 kilometers from Khor Al-Zubair channel, and the salinity concentration in the groundwater is eventual to many reasons, including the commixture of the groundwater to seawater, the septic containers, the aerosol particles impact from the sea as the source of Cl^- and Na^+, and the flow process from returning irrigation.

The case of the current study deals with the GALDIT application to evaluate the spatial vulnerability of hydrogeological settings within Dibdibba aquifer to IOSW. It can be carried out using hydrogeological, morphological, hydrodynamic, and chemical data (Djoudar Hallal et al., 2019). GALDIT approach aims to evaluate the vulnerable areas according to hazard degree categories, and set the percentage of intrusion impact on aquifer through the delineation of vulnerability maps in GIS environment of the areas within Khor Al-Zubair, Umm Qasr, and Safwan. The participation in an active way in the advancement of water resources plans by environmental monitoring and remediation aspects by modeling programs to assess the transport of salts to fresh water in coastal areas issue could perform remarkable management of water in the futuristic periods.

2. Study Area

The relevant surveyed area (RSA) inclusives Khor Al-Zubair, Umm Qasr, and Safwan and constitutes the vital sector where the groundwater is abundant but is being abused by inhabitants who undertake farming and animal rearing. The RSA is geographically positioned in Basrah overlooks its coast on the Arabian Gulf in its southeastern part at longitudes (47˚39'0"E-47˚57'0"E) and the latitudes (30˚6'0"N-30˚18'0"N), the land surface rises over 60 meters above sea level, particularly in the middle of area (Fig.1). The area is bounded in the north, east, and south by the Zubair, Khor Al-Zubair estuary, and Kuwait state boundaries, respectively; whereas the Arabian Gulf lies in the southeast side of the RSA. The Umm Qasr area has Iraq’s largest important port, which is divided into northern and southern harbors, while Khor Al-Zubair includes one large port in the south east, as well as petrochemical, fertilizer, and iron and steel factories.

3. Geological Setting

In general, the area is a flat plain with some places rising; it lies within Mesopotamian basin covered by sedimentary rocks of igneous sand and gravel, as well as uneven layers of clay that formed in an environmentally deltaic setting. The right border of RSA is represented by the Khor Al-Zubair estuary, which is a branch of the Arabian Gulf and a significant extension inside Iraqi lands with a length of 50 km. Sissakian et al. (2018) explained the drainage system near the Khor estuary represented fine dendritic which is an indicator of recent erosion activity. The Iraqi tectonic division clarifies that the area is a part of the unstable shelf and includes Basrah block, which is described with numerous lineaments that correspond with one another. The land is mainly tilted down from the southwestern to the northeastern (Buday, 1980). The deposition features on the large left and right sides of the area can be categorized into two types of quaternary deposits, alluvial fan and tidal flat deposits, respectively (Fig.2). The alluvial fan consists of gravely sand and sandy gravel, and it is a product of Wadi Al-Batin. It runs from the western south section near Iraq and Kuwait borders to the northeast parts, where it is deposited on the Dibdibba Formation (Al-Kubaisi, 1996).

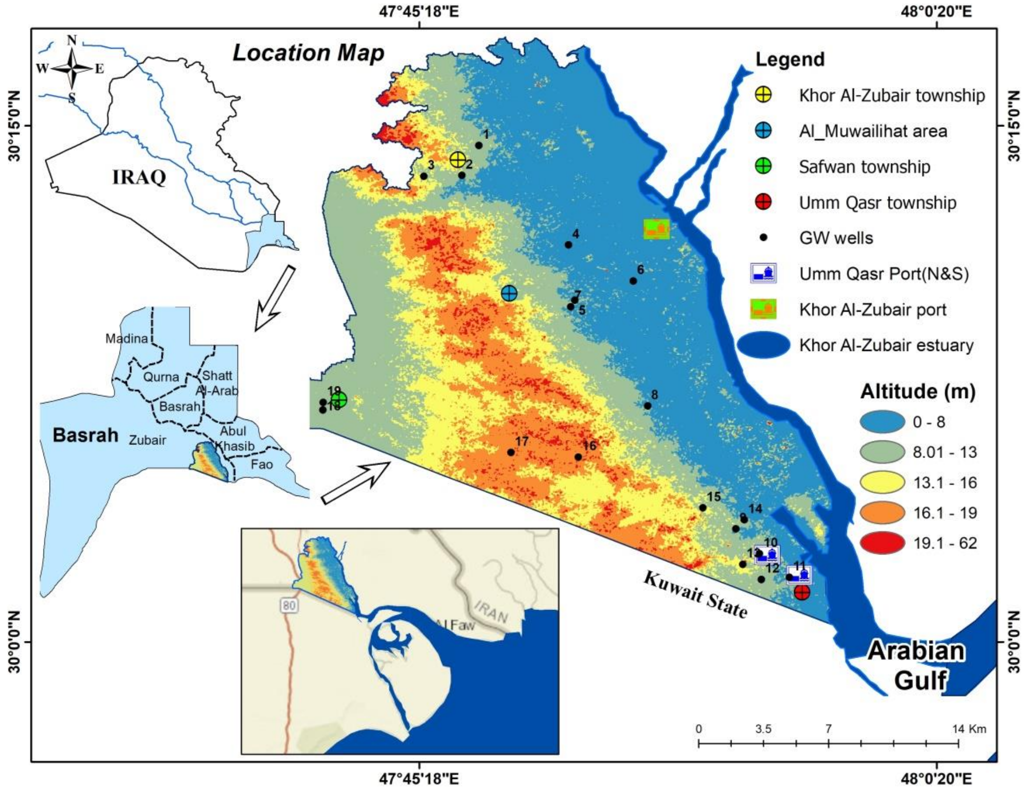


Fig.1. The RSA Location and elevation of earth surface map

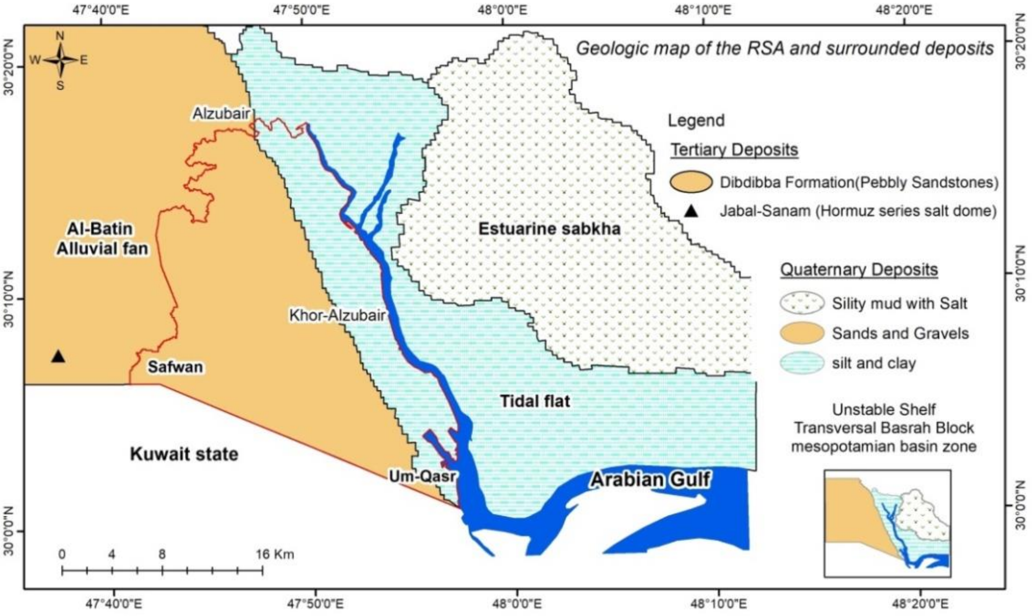


Fig.2. Geological map of the study area

4. Hydrogeological Setting

The RSA consists of two aquifer systems belonging to upper Dibdibba Formation. The first shallow unconfined involves deposition layers of sand and gravel. The second is deep confined to semi-confined system. The two aquifers contain two different hydrochemistry water, brakish and saline type respectively. The stiff clayey bed of 2 meter thickness is a barrier between them, its hydraulic conductivity reaches 0.38 m/day (Alkubaisi, 1996). The hydraulic conductivity of the Dibdibba aquifer ranges from 0.3-25.1 m/day and transmissivity is 15-265 m²/ day (Al-Jiburi and Al-Basrawi, 2009). The flow direction is from the western south to the eastern north with hydraulic gradient reached to 0.0018 (Fig. 3).

Several hydrogeological researches have thoroughly studied the southern part of Iraq within the Didibba aquifer include: the quantitative and qualitative determination of water resources and calculation of water budget (Al-Kubaisi, 1996), geochemical assessment of groundwater simulating and predicting of waterlogging by MODFLOW modeling (Al-Qurnawy and AlAbadi, 2019), The techniques of AHP-TOPSIS decision making to control the rise of the groundwater (Al-Abadi and Al-Qurnawy, 2021) and the statistical technique of multivariate in Zubair (Hussain et al., 2021).

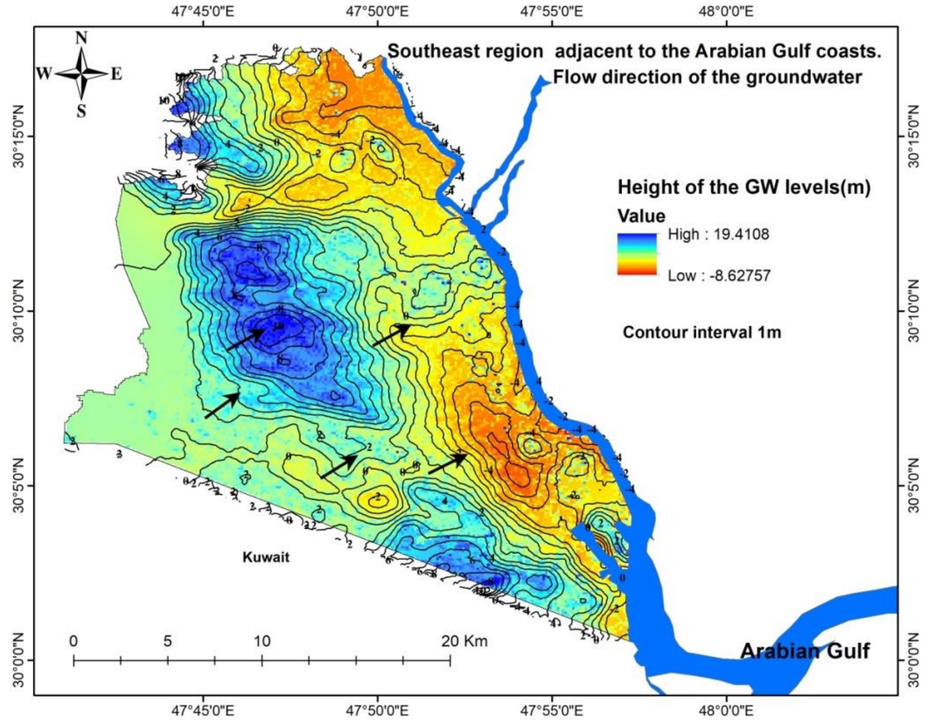


Fig.3. Flow direction of the groundwater (m)

5. Materials and Methods

5.1. Field Measurments and Water Sampling

Samples were collected from 19 wells distributed over the study area. Field measurements of depth to groundwater and electrical conductivity (EC) as in Table 2 were conducted through the wet and dry seasons of 2021 in order to detect the characteristics associated with the vulnerability of the aquifer. The chemical analyses of Na+, Cl^-, and SO_4^{2-} concentrations were tested by the Geochemical and Iraq Group For Science laboratories followed to Marine Science Center- University of Basrah) as in Table 3.The Flame photometry method to test the Na+, Titration by Mohr method for testing the Cl^-, and the Turbidimetric method for SO_4^{2-} to consider them within GALDIT method and statistically represented by SPSS software (Table 4).

Table 2. Field test of EC water samples and measurements of depth to groundwater in wells.

Samples	**Wet season**			**Dry season**		
	EC ms/cm	**TDS mg/l**	**Depth m**	**EC ms/cm**	**TDS mg/l**	**Depth m**
1	5.22	3340	8.9	5.08	3251.2	8.19
2	4.92	3156	11.13	4.62	2956.8	8.76
3	10.89	6969.4	14.64	11.7	7488	14.5
4	17.43	11155.2	2.54	17.9	11456	3.15
5	9.73	6226.5	8.01	9.34	6006.9	7.94
6	12.38	7936.8	2.96	12.64	8087.5	2.79
7	9.53	6100.5	7.62	9.15	5856	7.85
8	12.95	8341.3	7.65	13.98	8935.9	7.71
9	18.9	12103.5	9.63	19.72	12621	10.67
10	6.95	4472.3	10.48	7.9	5056	10.8
11	15.68	10039.9	4.5	16.09	10298	4.83
12	9.59	6139.5	7.95	9.4	6016	8.25
13	7.13	4567	7.5	7.67	4908.8	9.47
14	17.5	11197	9.68	20	12800	10.53
15	18.4	11768.2	13.26	20.2	12928	13.61
16	11.8	7552	18.48	13.51	8646.4	18.46
17	10.3	6593	18.32	9.8	6272	18.6
18	11.19	7167.5	10.76	13.15	8399.3	10.99
19	11.2	7167.9	10.62	13.14	8409.6	10.98

Table 3. Laboratory chemical tests of water samples.

Samples	**Wet season**			**Dry season**		
	Na$^+$ mg/l	**SO$_4^{2-}$ mg/l**	**Cl$^-$ mg/l**	**Na$^+$ mg/l**	**SO$_4^{2-}$ mg/l**	**Cl$^-$ mg/l**
1	305	1732.4	728.1	520	1693	728.7
2	298	1757	595.6	301	1783	595.5
3	1500	3137	1788	2103	3431	2052.2
4	2260	3889	3707	2998	5293	3972
5	1140.8	2720.5	1707.2	1306.4	2770	1842.7
6	1670.5	3094.9	2419.5	1993.2	3484.4	2584.8
7	1105	2692	1655	1258	2713	1788
8	2201.03	3181.9	2585.5	2339.3	2945.3	2739.2
9	3725	3741	3641	3560	5584	4170
10	1110	2491	993	1125	1799	1125.4
11	2490	2963	3244	2520	4702	3641
12	1415	2867	1324	1385	2814	1390.2
13	750	2147	994.4	848	2216	1257.8
14	3380	3399	4039	3663	6128	4634
15	3620	3495	4766	3562	2015	4632
16	1940	3617	1920	2405	1824	2118.4
17	1940	2570	2052	1452	1778	1655.1
18	1779.2	2221.7	1855.9	1466.4	3509.7	2446.6
19	1780	2216	1854	1463	3517	2449.4

Table 4. Descriptive statistics of the chemical contents of groundwater in wet and dry seasons

Statistical Elements	**Wet season**				**Dry season**			
	TDS	**Na^+**	**SO_4^{2-}**	**Cl^-**	**TDS**	**Na^+**	**SO_4^{2-}**	**Cl^-**
Mean	7473.5	1811	2838.5	2203.6	7915.4	1909	3157.8	2411.7
Median	7167.5	1779	2867	1855.9	8087.5	1466	2814	2118.4
Min	3156	298	1732	595.6	2956.8	301	1693	595.5
Max	12103.6	3725	3889	4766	12928	3663	6128	4634

5.2. GALDIT Model

For the first time in India, (Chachadi and Lobo-Ferreira, 2001) discovered GALDIT approach for estimating the aquifer vulnerability index. The acronym GALDIT is derived from the acronyms of the following six parameters: Groundwater occurrence (G), aquifer hydraulic conductivity (A), height of groundwater level above sea level (L), distance from the shore (distance inland perpendicular from shoreline) (D), impact of existing status of seawater intrusion in the area (I), and the thickness of the aquifer (T). Fig. 4 shows the procedures of GALDIT modeling that are arranged according to the availability of RSA hydrogeological information.

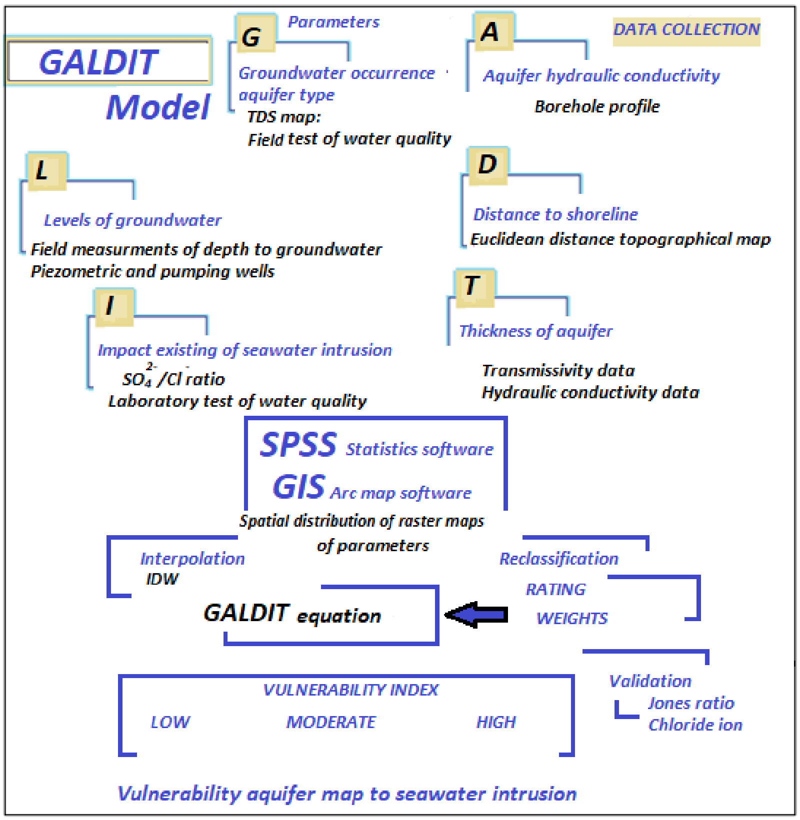


Fig.4. Flowchart of the RSA vulnerability aquifer to seawater intrusion

This manner of modeling appraises the prediction of the extent to which wells in coastal aquifers are exposed to intrusion by seawater (Bouderbala et al., 2016). The model explains how the numerical ranking method depends on overlay and index procedures (Chang et al., 2019). The concept of modeling shows that six basic parameters have theoretically assessed weights and ratings that demonstrate estimative importance to the IOSW as explained in Table 5.

Table 5. Typical GALDIT rating and weights (Chachadi and Lobo-Ferreira, 2001)

Parameter	Weights	Very low rating	Low rating	Medium rating	High rating
G	1	Bounded	Semiconfined	Unconfined	Confined
A	3	< 5 m/d	5-10 m/d	10-40 m/d	> 40 m/d
L	4	> 2m	1.5-2 m	1-1.5 m	< 1 m
D	4	> 1000m	750-1000m	500-750m	< 500m
I	1	< 1	1-1.5	1.5-2	> 2
T	2	< 5m	5-7.5	7.5-10m	> 10m

The spatial distribution maps of parameters have been arranged and combined according to their classification, modified rating, and weights as in Table 6. Each parameter was made in the form of a raster thematic map to generate a spatial distribution that comprises the minimum and maximum influential values.

Table 6. Modified rating and ranking applied for modeling

Parameter	Classification	Rating
G	Confined to Semi-confined	10
	Unconfined	7
A	6-8 m/d	4
	8-10 m/d	5
	10-22 m/d	6
L	<1 m	10
	1-1.5 m	7
	1.5-2 m	5
	>2 m	2
D	<500 m	10
	500-750 m	7
	750-1000 m	5
	>1000 m	2
I	<1	10
	1-1.5	7
	1.5-2	5
	>2	2
T	>10	10

The calculation of the GALDIT index vulnerability explained in Equation1 (Chachadi and Lobo-Ferreira, 2001). GALDIT index can be classified into three parts according to the risk degree: high (>7.5), moderate (5-7.5) and low (<5).

$$\text{GALDIT index} = \frac{\sum_{i=1}^{6}(Wi * Ri)}{\sum_{i=6}^{6} Wi} \qquad (1)$$

Where Wi is the weight of the i indicator, R is the rating or importance value of the I. All parameters were subjected to interpolation and reclassification by application of Arc Map GIS software version 10.3 to classify vulnerability according to the effect IOSW. The final vulnerability maps are created by the raster calculator tool using formula 2 (Lappas et al., 2016):

$$GALDIT\ index = \mathrm{G} + 3\mathrm{A} + 4\mathrm{L} + 2\mathrm{D} + \mathrm{I} + 2\mathrm{T}/13 \qquad (2)$$

6. Results

6.1. Spatial Distribution of Parameters

6.1.1. Groundwater occurrence or type of aquifer (G)

The evolution of this parameter for IOSW corresponds to several factors in keeping with class of aquifer. The unconfined aquifer is susceptible to intrusion in natural condition compared to semi-confined aquifer (Trabelsi et al., 2016), it bears a pressure less than atmospheric pressure, making it affected, besides the absence of an upper impermeable layer. However, due to overexploitation by pumping, the confined aquifer is more prone to seawater than the unconfined aquifer, which leads to greatest cone of depression (Djoudar Hallal et al., 2019; Motevalli et al., 2018). Semi-confined aquifers are less exposed compared to unconfined and confined aquifers, because they maintain the smallest hydraulic pressure by leakage from bordering aquifers (Saidi et al., 2014).

The major aquifers dealing with the RSA within the Dibdibba Formation can be categorized into two classes: upper unconfined aquifers with a total dissolved solid (TDS) of less than 10,000 mg/l and lower confined to semi-confined aquifers with a TDS of more than 10,000 mg/l (Abdulameer et al., 2021; Al-Kubaisi, 1996). The required rating of the type of aquifer was established according to the TDS data that ranges from 3153- 12104 mg/l for the wet season and 2960-12928 mg/l for the dry season, as shown in Fig. 5a and b respectively, which indicate the increasing salinity. The spatial distribution of TDS that has scored from 3000 mg/l to 10,000 mg/l was classified as brackish water (moderately saline). It was estimated to be an unconfined class and got a 7 rating. The remaining areas that have a high salinity of more than 10,000 mg/l are classified as saline to brine water. They were estimated to be confined to a class and gained a rating of 10.

6.1.2. Aquifer hydraulic conductivity (A)

It refers to a soil's or rock's ability to transfer water when subjected to a hydraulic gradient, because there is a direct relation between IOSW and hydraulic conductivity, the vulnerability issue becomes more intensive as hydraulic conductivity rises, increasing water movement and hence pollutant and salt transfer(Gangadharan and Rekha, 2015). As shown in Fig. 5c, this indicator is only measured for the RSA within the Dibdibba aquifer, with spatial distribution values ranging from 1.3 to 28 m/d.The coastal areas of Umm Qasr reached intermediate ranges, considered rating 6 as a moderate score vulnerable to marine intrusion.

6.1.3. Height of the Groundwater (L)

When the groundwater rises, water pressure is generated to thrust back the seawater front and thus prevent it from intruding into aquifers. The high vulnerability of IOSW occurs when the groundwater level is lower than the seawater level (Gnanachndrasamy et al., 2019). The Ghyben- Herzberg theory states that 40 meters of freshwater are situated below sea level, down to the interface, when every meter of freshwater is stocked above mean sea level (Mirzavand et al., 2018). The aquifers which located near coasts have the lowest water levels above sea level due to excessive pumping of their wells and thus have the largest impact of vulnerability state (Seenipandi et al., 2019).

Within the relevant surveyed area, measurements of water levels had done by the researcher were carried out throughout a year, and an increase in depth to groundwater was observed in dry season. The depth was measured to vary from 2.5 - 18.5 m and 2.8-18.6 m through wet and dry seasons, respectively, which explains the decrease in groundwater levels of about 15 to 35 cm in the dry period through six months from January to Jone. The height of the groundwater level for wet and dry seasons was shown in Fig. 5d and e, respectively. The coastal lands of Umm Qasr and Khor Al-Zubair have low levels of the groundwater. The lower the groundwater level has the greater the impact of IOSW owing to the inverse relation, and thus taking 10 rating to explain more vulnerable with seawater, while the high-lying topographic area in the middle of the study area is less vulnerable. The L map was obtained by subtracting the depth to groundwater map from the Digital Elevation Model (DEM) map using the raster calculator spatial analyst (Idowu et al., 2016).

6.1.4. Distance to the shoreline (D)

Another required parameter which has high value of weight was involved in the GALDIT equation in order to calculate the distance of extension from the well location to coastline. In general, the closer wells to the shoreline have a greater impact of marine intrusion (Bouderbala et al., 2016). It can be estimated from topographic data maps (Lappas et al., 2016). The coastal areas of Um Qasr and Khore Al-Zubair are the closest areas to seawater of Khor Al-Zubair channel (Fig. 5f), thus, they are more affected by the IOSW and get a 10 rating, in contrast to the farthest area from the coast, represented by Safwan.

6.1.5. Impact of the existing status of sea water intrusion (I)

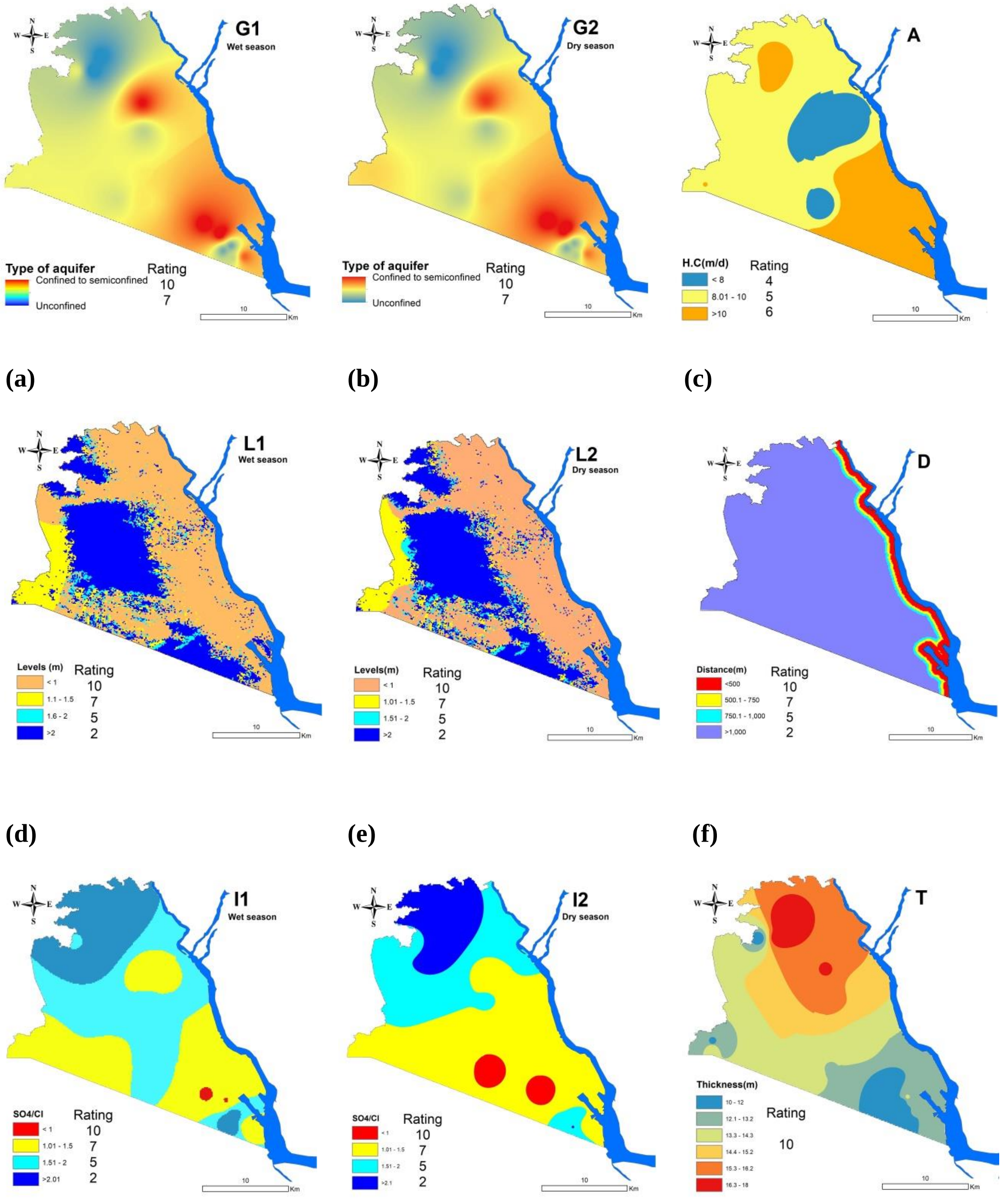
The ratio of SO_4^{2-} to Cl^- was used for the determination of I factor (Saaidi et al., 2014). The irregular and intensive pumping from wells will cause excessive pressure on aquifers, thereby creating an imbalance between the groundwater and marine water. Such cases generate decreasing piezometric levels and, consequently, allow increasing seawater intrusion (Tasnim and Tahsin, 2016). For the RSA, the ratio extracted from laboratory chemical analyses such SO_4^{2-}/Cl^- used in the GALDIT equation. The inverse relation between I and IOSW and rating assigned to it, in other words, low values of I that are less than 1 are classified as a high rating of 10, indicating the presence of marine water, and the classification is reversed because of the existing chloride concentration in the denominator. The spatial distribution of this ratio varies among the three regions for wet and dry seasons explained in (Fig. 5g and h) respectively, where the low values of SO_4^{2-}/Cl^- are shown in some parts of Umm Qasr.

6.1.6. Thickness of aquifer (T)

The saturated thickness of an aquifer is a magnificent parameter for detecting the impact of seawater. The relationship between saturated thickness and seawater influence is direct, in another words, increasing saturated thickness greater than 10 meters explains increasing vulnerability (Mavriou et al., 2019). The depth of saturated media of all RSA within Dibdibba aquifer exceeds 10 meter, so the effect of vulnerability scored 10 the highest rating (Fig. 5i). The saturated thickness of aquifer in Khor Al-Zubair reduces sequentially towards the southern part of Um Qasr. This indicator was calculated by the transmissivity which is a product of hydraulic conductivity with the saturated thickness of aquifer.

6.2. Synopsis of Statistics

All the parameters were evaluated statistically by IBM SPSS software version 26 (Table 7). It was appointed to test the normality distribution of GALDIT modeling. The normal Q-Q plot of parameters displayed field and laboratory results (Fig. 6), as well as survey report data as observed and expected variables to test the accuracy relative to reality for preparing the model.



(a) **(b)** **(c)**

(d) **(e)** **(f)**

(g) **(h)** **(i)**

Fig.5. Spatial distribution of GALDIT parameters

Table 7. SPSS statistics for the parameters used in the GALDIT modeling

parameters	Impirical weight	Mean	Meadian	Standard deviation	Min	Max
G	1	7473.5	7167.5	2733.5	3156.03	12103.6
A	3	12.25	10.5	5.18	5	22.22
L	4	1.195	1.01	2.29	-4.04	6.58
D	2	8023.57	7481.23	4675.19	1407.49	16308.39
I	1	1.59	1.49	0.62	0.73	2.95
T	2	13.55	13.47	2.33	10.03	18.04

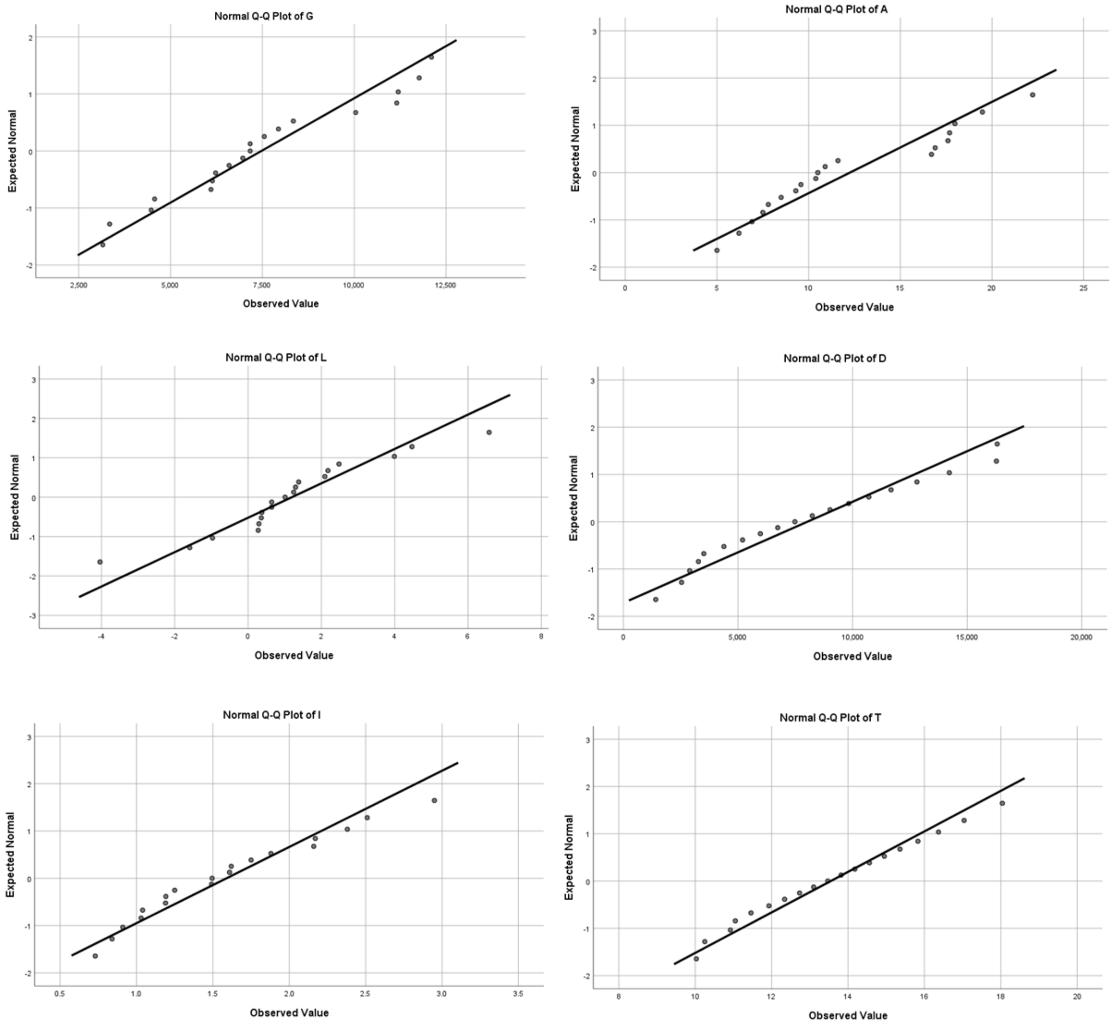


Fig.6. SPSS statistics for observed and expected distribution of GALDIT parameters.

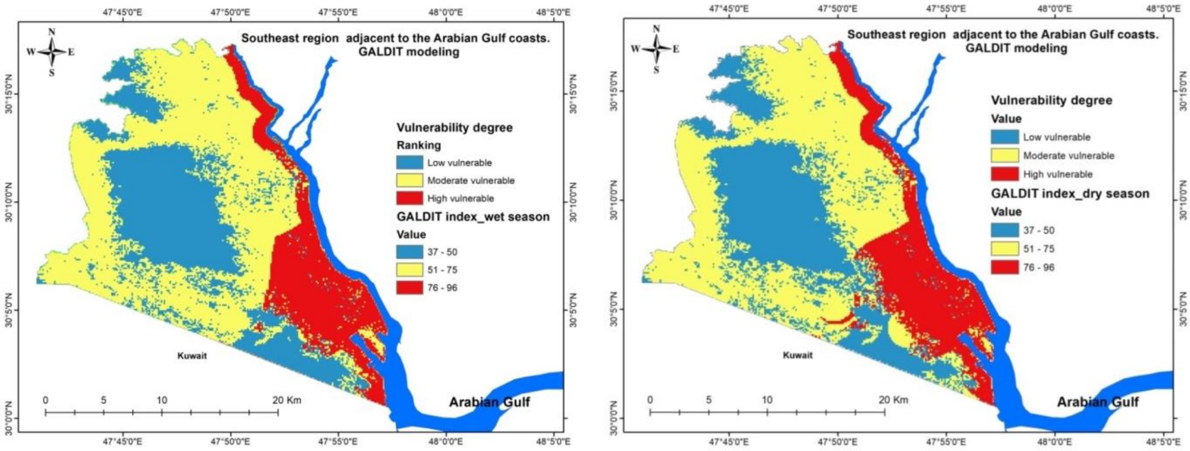
The GALDIT degrees were then classified into three categories: low, Moderate, and High vulnerable to reveal the vulnerability of aquifer distribution for wet and dry periods respectively as in (Table 8) and (Fig. 7. a and b). The low class covers 139.65km² (33.11%) and 142.61km² (33.81%), the moderate class covers 205.21km² (48.65%) and 196.61km² (46.61%), and the high class covers 76.87km² (18.23%) and 82.56km² (19.57%), respectively

Table 8. Distribution of vulnerability aquifer to seawater intrusion according to degree and score

GALDIT score	Vulnerability degree	Area (Km²) wet	Area %	Area (Km²) dry	Area %
<5	Low	139.65	33.11	142.61	33.81
5-7.5	Moderate	205.21	48.65	196.61	46.61
>7.5	High	76.87	18.23	82.56	19.57

6.3. Validation of Vulnerability Maps

In order to evaluate the accuracy and validation of vulnerability model maps, Jones ratio and chloride concentrations were used to determine the potential effect of seawater intrusion to the situation of aquifer. Spatial distribution of both parameters was mapped as follows:



(a) (b)

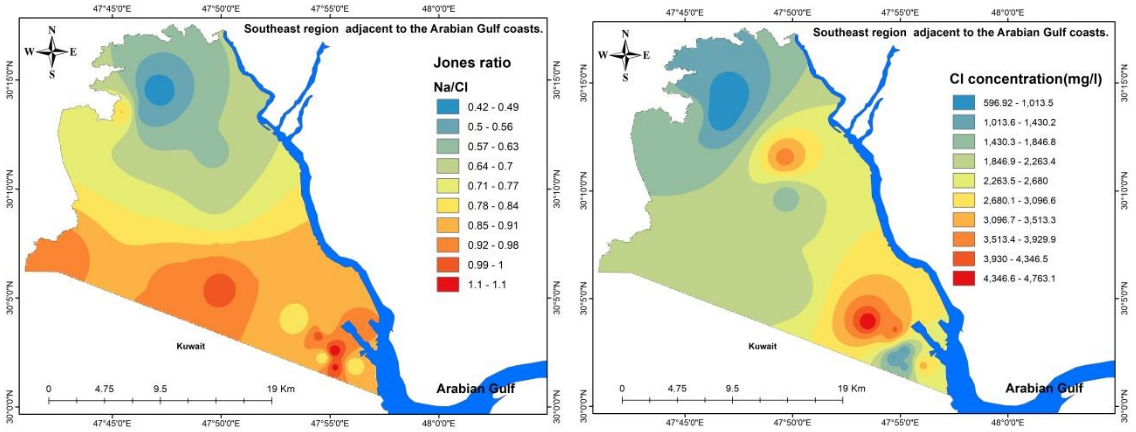
Fig.7. Vulnerability aquifer to seawater intrusion for (a) wet season; (b) dry season.

6.3.1. Jones ratio (JR)

It represents sodium to chloride concentrations as Na^+/Cl^- ratio, for distinguishing between the source of salinity of clay materials, household waste and sewage from the source of salinity by seawater. It could be argued that a JR ratio higher than 1, indicates that the source of groundwater salinity comes from the household waste or sewage or ion-exchange with clay. If the JR scores less than 0.86, the source of salinity comes from the effect of seawater intrusion (Trabelsi et al., 2016). For the current study, the ratio of JR ranges from 0.4 to 1.1, ratio below 0.86 was noticed within the south and southeast sides of the studyarea of Um Qasr and Khor Al-Zubair wells as shown in Fig. 8 a.

6.3.2. Chloride concentration (Cl^-)

One of the most obvious signs of seawater impact is the increased concentration of chloride ion in the groundwater. The spatial distribution of Cl^- varies from 595.6-4766 mg/l. High chloride values are concentrated in Um Qasr and Khor Al-Zubair areas as in Fig. 8b.



(a) (b)

Fig.8. Validation for (a) Jones ratio (B) Chloride concentration

7. Discussion

The magnificent tool of GALDIT modeling applies for assessing and diagnosing areas at risk of marine extension towards the aquifer. GALDIT maps for wet (January) and dry (June) periods indicated three levels of aquifer vulnerability; high vulnerability, particularly in the south-east part of the relevant surveyed area represented by Umm Qasr and the closest distances of Khor Al-Zubair to the shoreline; moderate vulnerability towards the western and northern sides comprising Safwan and the rest of Khor Al-Zubair far away from the shoreline; and finally low vulnerability in the central part which is called Al-Muwailihat area that lies between Khor Al-Zubair and Safwan area, the high topographic area. The percentage of high vulnerability reached to 18.23% in wet period, while it increased to 19.57% after six months in dry period, as it was interpreted by decreased levels of the groundwater owing to reduced recharge rate and rainfall besides excessive pumping for industrial and agricultural usages. The factors A, D, and T are considered to have constant values in both seasons, while G, L, and I have seasonally changes. A rise in TDS levels during the wet period appeared in Umm Qasr wells, especially 14, 15, and 9, where the EC values were recorded 17.5 ms/cm, 18.4 ms/cm and 18.9 ms/cm respectively, as for Khor Al-Zubair wells 2 and 1, they recorded low salinity values that reached 4.92 ms/cm and 5.22 ms/cm. In comparison with the dry period, EC showed a noticeable increase and reached 20 and 20.2 ms/cm in wells 14 and 15 within Um Qasr area, while the lowest value was scored in well 1, at 5.08 ms/cm. Depth to groundwater was noticed in Khor Al-Zubair wells 4 and 6. It reached to 2.54m and 2.96 m in wet periods, respectively, but the high depth observed in Um Qasr-Safwan road from wells 17 and 16 for the same periods reached to 18.32m and 18.48m, respectively. As for the dry periods, low depth in wells 6 and 4 reached to 2.79m and 3.15m, and highest depth in wells 16 and 17 was 18.46m and 18.6m within Um Qasr-Safwan area. Levels of groundwater had an inverse relationship with the and, likewise, factor I represented the ratio of SO_4^{2-} /Cl^-. The lack of this ratio indicates increased seawater intrusion. The lowest value of SO_4^{2-}/Cl^- in well 15 was 0.43in the dry season, which is less than the value 0.73 in wet season for the same well. In contrast, the highest SO_4^{2-} /Cl^- value was in Khor Al-Zubair wells 1 and 2 which reached 2.37, 2.3, 2.95, and 2.99 in wet and dry seasons, respectively. Jones ratio (Na^+/Cl^-) and chloride concentration were applied for validating the vulnerability of aquifer maps. The ratio of JR was less than 0.86 in some parts of Um Qasr and Khor Al-Zubair wells, while the high values of the chloride concentration were in Umm Qasr wells.

8. Conclusions

Several factors impact aquifer vulnerability by seawater intrusion, a decrease of peizometric levels by overexploitation for irrigation and other uses, poor recharge, low rainfall, climate change with expected sea level rise and intense drought hence to change the quantity and quality of the groundwater. The present study applied the GALDIT model for the first time in Iraq. Mapping of the model was prepared by GIS environment within relevant surveyed area of Khor Al-Zubair, Um Qasr, and Safwan, which belong to the Dibdibba aquifer southeast of Iraq. Parameters were applied to calculate the vulnerability index namely hydrogeological data the height of groundwater level above sea level besides hydraulic conductivity and thickness of aquifer, morphological data represented perpendicular distance to shoreline, and chemical data such as ion concentrations of Chloride, sulphate, and sodium. The application for the current study indicated the presence of seawater intrusion in some areas. GALDIT index results show three classes of aquifer vulnerability appeared in relevant surveyed area, the low vulnerable areas occured in Al-Muwailihat area, which rises slightly topographically and located between Khor Al-Zubair and Safwan, moderate vulnerable areas occurred in Safwan and the far distances to shoreline, and the risk degree of high vulnerable areas comprised Um Qasr, which has the shortest distance to coastline. Through intensive environmental monitoring of wells, modelling programs can contribute to water resources management plans to prevent aquifers from being contaminated by seawater intrusion within the coastal areas.

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